TURBO-FFT: ACCELERATED FAST FOURIER TRANSFORM FOR HIGH-SPEED 5G COMMUNICATION SYSTEMS

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Abstract

The rapid growth of 5G communications demands faster and more efficient signal processing to support high-speed data transmission. Fast Fourier Transform (FFT) plays a crucial role in various aspects of 5G networks, including spectrum analysis, channel estimation, beamforming, and equalization. Its ability to analyze signals in real time makes it essential for emerging applications such as the Internet of Things (IoT), autonomous vehicles, and virtual reality. Traditional signal processing methods used in 4G networks often struggle to keep up with the massive data loads, leading to inefficiencies and increased latency. As data consumption continues to soar, there is a pressing need for advanced techniques to enhance signal processing capabilities. This study explores how FFT can revolutionize 5G networks by improving spectral efficiency, reducing latency, and optimizing overall system performance. By integrating FFT into different aspects of 5G signal processing, we aim to create a more responsive and reliable communication infrastructure. The study provides an in-depth analysis of FFT's potential to transform wireless communication by enabling faster and more accurate data processing. With the increasing demands of modern applications, leveraging FFT in 5G networks can help overcome existing challenges and ensure seamless connectivity. As 5G technology continues to evolve, FFT's role in optimizing network efficiency and real-time processing will be instrumental in shaping the future of wireless communications.

Keywords: Fast Fourier Transform, Discrete Fourier Transform, Orthogonal Frequency Division Multiplexing, Very Large-Scale Integration

1.Introduction

James Cooley and John Tukey independently developed an algorithm known as the Cooley-Tukey FFT algorithm. Fast Fourier Transform (FFT) is an algorithm used to efficiently compute the discrete Fourier transform (DFT) and its inverse. DFT is a mathematical technique that transforms a signal from its time domain representation to its frequency domain representation, which provides insights into the frequency components present in the signal. This algorithm exploits the periodicity properties of complex exponentials to recursively divide the DFT computation into smaller sub-problems, significantly reducing the number of arithmetic operations required for computation. The FFT is not only a widely used algorithm in various technologies, but it was also discovered by scientists trying to detect covert nuclear weapons tests, highlighting its significant impact beyond signal processing. Real-world signals are not infinite and continuous, but finite and made up of individual samples or data units, leading to the need for a DFT. In the context of 5G, FFT is used for OFDM (Orthogonal Frequency Division Multiplexing) modulation/demodulation. OFDM's ability to handle high data rates and spectrum efficiency makes it a key component in 5G. FFT allows for the rapid conversion of signals between time and frequency domains, facilitating the handling of multiple subcarriers simultaneously. The deployment of FFT in 5G systems has significantly enhanced data transmission speed, spectral efficiency, and overall performance, contributing to the evolution of wireless communication technologies.

2.Literature Survey

Morselli et al. [1] emphasize the necessity of precise location data for new applications in 5G. Despite ongoing advancements, meeting strict 3GPP standards remains a hurdle. Their work reviews standardized signals and introduces a soft information-based method, showing superior performance, especially in challenging conditions, heralding progress for 5G and beyond networks. Khandelwal et al. [2] advocate for NOMA in 5G due to its spectral efficiency and ability to meet connectivity demands. They integrate NOMA with OFDM, employing QAM modulation and FFT encoding for optimized power allocation using the firefly optimization algorithm, yielding superior SNR, BER, SE, and EE outcomes compared to traditional techniques.Lynch et al. [3] propose a 5G/mm-Wave harmonic FMCW radar system for precise CPS localization. Their fully passive harmonic mmID technology offers long-range detectability, achieving highly accurate ranging up to 46m with 17cm maximum error and ultrafine 0.4mm accuracy at 10m, paving the way for fully-passive, long-range ranging systems in future CPSs.Baskaran et al. [4] delve into optical networking in 5G, addressing capacity and latency needs. They discuss the evolution of optical segments and propose solutions for reliable, low-latency services, including reconfigurability and security enhancements using machine learning and software-defined networking concepts.

Molodtsov et al. [5] introduce trainable FFT structures to enhance beamspace transformation accuracy in MU Massive MIMO receivers. Their approach mitigates performance loss in MU signal detection, outperforming fixed and other trainable FFT methods, aiming to boost the efficiency of beamspace transformation critical for multi-user Massive MIMO systems. Bychkov et al. [6] propose DFT-based beamspace selection algorithms for MIMO receivers in realistic MU scenarios, addressing power imbalances and implementing proportional fair resource allocation. Their methods outperform other DFT-based alternatives in simulations, demonstrating improved performance in coverage and capacity with feasible implementation complexity.Barrios-Ulloa et al. [7] highlight the slow deployment of 5G in Latin America, particularly in Colombia, due to spectrum availability issues and delays in auction processes. Despite government and operator efforts, standalone 5G is not expected in Colombia before 2023, hindering advancements in ultrahigh-reliability, low-latency, and enhanced mobile broadband services.Wei et al. [8] introduce Integrated Sensing and Communication (ISAC) as a key technology for 5G-A and 6G systems, emphasizing its high spectrum efficiency and low hardware cost. They address challenges in ISAC signal design and processing, proposing phase coding for improved anti-noise performance and iterative processing methods for energy-efficient sensing.Srinivasan and Thanikaiselvan [9] discuss channel estimation in wireless communication, emphasizing the importance of removing noise and distortions added during signal transmission. They propose a novel channel estimation approach leveraging deep learning techniques to improve accuracy and reduce computational complexity in MIMO-OFDM systems.

Wang et al. [10] focus on IoT applications in 5G communications, particularly UCA-based OAM communication. They propose a phase calibration scheme for distributed UCAs to mitigate phase deviation and improve communication performance. Simulation results demonstrate the effectiveness of the proposed scheme in enhancing uplink communication capacity for distributed IoT end nodes. Silva et al. [11] emphasize the importance of understanding EMC requirements in the context of 5G, providing insights into certification processes and test methodologies. They discuss challenges in EMC test facility setup, offer guidance on equipment selection for RF conformance tests, and explore the potential impact of 6G advancements on EMC.Chen et al. [12] discuss the progress and future directions of 5G-Advanced standardization, highlighting its role in expanding 5G capabilities and accommodating diverse use cases. They provide an overview of state-of-the-art technologies investigated in 3GPP Release 18, paving the way for further research and development towards 6G.

Yao et al. [13] propose an improved TOA estimation algorithm for 5G NR signals under multipath environments, achieving high resolution and accuracy. Their algorithm utilizes MVDR with a novel smoothing scheme and denoising method, outperforming traditional beamforming techniques like Bartlett BF.Guo et al. [14] introduce a TST method for linear sampling of interference signals in RFTURS for atmospheric CO2 detection. Their approach addresses drawbacks of existing methods and provides guidance for field measurement of atmospheric CO2, enhancing the accuracy of RFTURS measurements. Li et al. [15] present a low-latency STFT processing scheme based on microwave photonic processing, enabling real-time and high-speed spectral dynamic analysis for non-stationary signals. Their approach achieves high temporal resolution and instantaneous bandwidth, capturing transient information with minimal processing latency.

3.Proposed Methodology

The FFT is a fundamental algorithm used in various fields as shown in Figure 1, including signal processing, image processing, and data analysis, to efficiently compute the Discrete Fourier Transform (DFT) of a sequence or signal. The DFT converts a signal from its time or spatial domain representation into its frequency domain representation, revealing the frequency components present in the signal. FFT significantly accelerates this computation compared to the standard DFT algorithm, making it feasible for real-time and large-scale applications. At its core, FFT exploits the symmetry and periodicity properties of sinusoidal waves to decompose the DFT computation into smaller sub-problems, resulting in a drastic reduction in computational complexity. By recursively dividing the input data sequence into smaller subsets, FFT transforms the original N-point DFT computation into a series of smaller DFTs, each of size N/2, N/4, N/8, and so on. This divide-and-conquer strategy, combined with clever indexing and butterfly operations, enables FFT to achieve a time complexity of O(N log N), compared to the O(N^2) complexity of the standard DFT algorithm for N-point sequences.

Furthermore, FFT exhibits excellent parallelizability, making it highly suitable for implementation on modern computing architectures, including multi-core CPUs, GPUs, and specialized hardware accelerators like FPGAs and ASICs. Parallel FFT algorithms exploit parallel processing units to compute DFTs of smaller subsets concurrently, further enhancing the algorithm's efficiency and scalability. In addition to its computational efficiency, FFT finds widespread applications in various domains. In signal processing, FFT is commonly used for spectral analysis, filtering, and modulation/demodulation tasks. In image processing, FFT plays a crucial role in tasks such as image enhancement, compression, and pattern recognition. Moreover, FFT is extensively utilized in scientific computing, telecommunications, audio processing, and many other fields where frequency domain analysis is essential.

Despite its numerous advantages, FFT has certain limitations and considerations. The choice of FFT variant (e.g., radix-2, radix-4, mixed-radix) depends on factors such as input data size, hardware constraints, and desired computational efficiency. Additionally, care must be taken to address issues like spectral leakage, aliasing, and boundary effects that may arise during FFT-based processing. Overall, FFT remains a cornerstone algorithm in signal and image processing, offering unparalleled efficiency and versatility in analyzing and manipulating frequency-domain data.

Step 1:Consider digital data as input data. The input index vector generator operation is to store the input data and assigning the vector address to the input data and it also performs as counter it count each and every input sequence and it map input to output. Here there are two memory banks are present in this the input data can store.

Step 2:Here there are two main problems one data can store in multiple memories and one address for multiple data these are major disadvantages by this overlapping may occur to reduce this problem or to correct this problem we have taken computing generator.

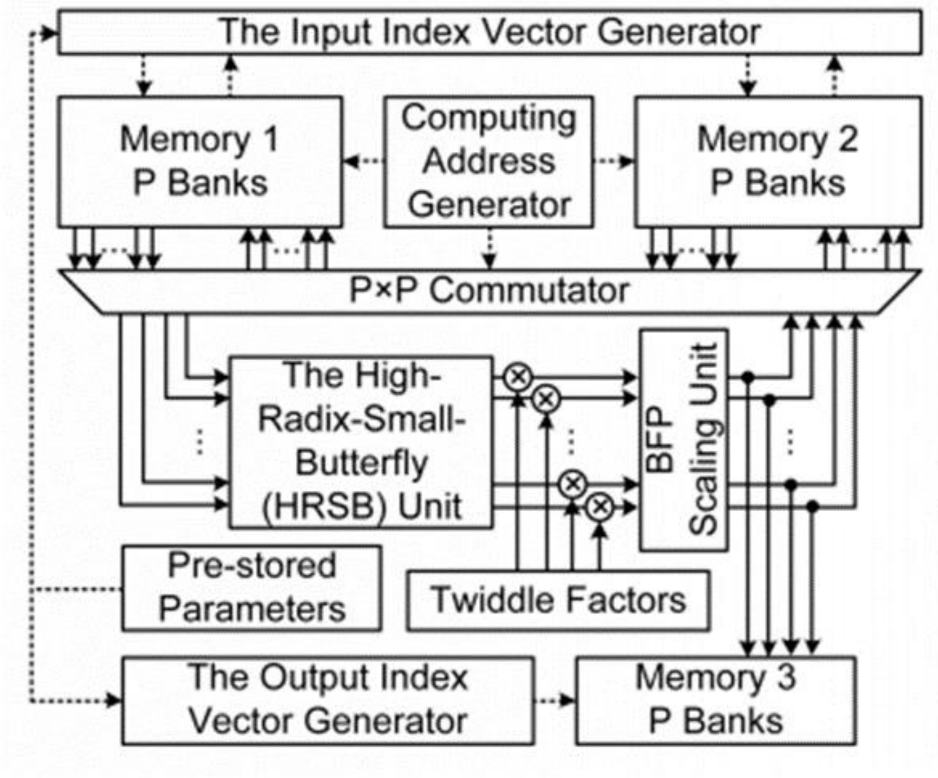


Figure 1. Proposed FFT Architecture

Step 3:The operation of computing generator is to assign one data in one memory bank this totally monitor all the data, address, and it totally avoids the overlapping.

Step 4:p*p Commutator this performs as cross couple generator unit and it divides paths and sub paths of each butterfly unit by using p*p commutator and it acts as crossbar switching network and its also responsible for packet or data sharing.

Step 5:HRSB here p*p commutator divides all the butterfly unit and the major problem is we get large no. of adders and multipliers and the output is never ending loop to rectify this problem HRSB maintain all the butterfly units with equal size and the maximum size of the butterfly is 2*2butterfly unit and 4*4 butterfly unit if radix is high then automatically complexity is high to avoid this small butterfly units are preferable.

Step 6:Twiddle factor is a trigonometric constant coefficient that are multiplied by the data in the course of the algorithm.

Step 7:Butterfly Product Scaling operation of BFP scaling is multiplication operation between input data to twiddle factors and multiplication output are applied to final memory to implement high speed feedback and full fill overall FFT operation .after all the final data will store in final memory bank by using output index vector generator.

Step 8:Output index vector generator is generating the output addresses in synchronization with input address .

Step 9:Memory bank 3 will store the final FFT operation as output.

4. Result and Discussion

Figure 2 represents the outcome of simulating both the existing and proposed FFT implementations. Figure 3 provides a design summary of both FFT implementations. Table 1 presents a comparison table between the existing FFT implementation and the proposed FFT implementation across various metrics. The metrics listed include the number of Look-Up Tables (LUTs), Digital Signal Processors (DSPs), and Input/Output (IO) ports utilized by each implementation. The comparison highlights the differences in resource utilization between the two implementations, with the proposed FFT requiring fewer resources (lower LUTs and DSPs) while maintaining the same number of IO ports.

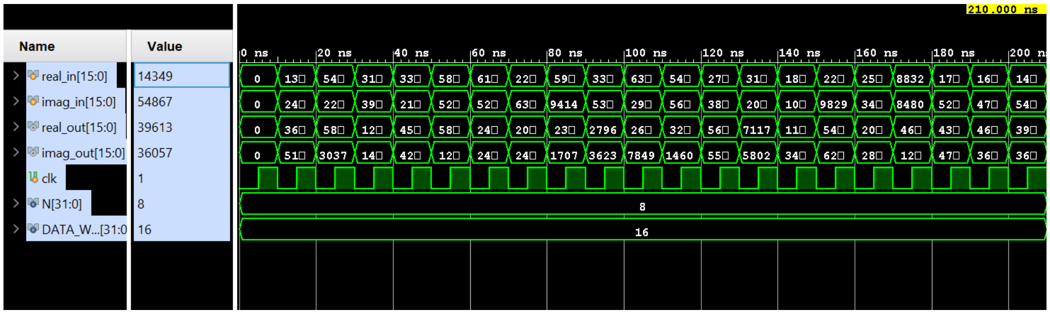
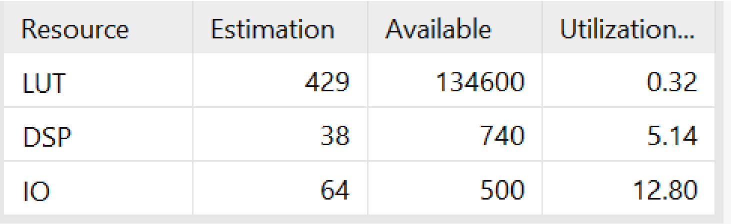


Figure 2. Simulation Outcome.



Resource	Estimation	Available	Utilization...
LUT	429	134600	0.32
DSP	38	740	5.14
IO	64	500	12.80

Figure 3. Design summary.

Table 1. Comparison Table.

Metrics	Existing FFT	Proposed FFT
LUT	734	429
DSP	65	38
IO	64	64

5. Conclusion

The FFT revolutionized DSP by providing a highly efficient method for computing the DFT. Its algorithmic complexity of O(N log N) compared to the O(N^2) complexity of direct DFT computation enabled rapid analysis of large datasets, making real-time processing feasible across various fields. This efficiency, coupled with its accuracy, versatility, and wide-ranging applications, solidifies FFT as a cornerstone in modern signal processing. From audio and image processing to communication systems and scientific research, FFT plays a pivotal role in extracting meaningful information from signals, paving the way for advancements in technology and scientific discovery. Despite its computational efficiency, implementing FFT algorithms requires careful consideration of factors such as data size, memory constraints, and desired precision. Choosing the appropriate FFT variant, such as radix-2, radix-4, or mixed-radix algorithms, depends on the specific requirements of the application and the available computational resources. Additionally, optimizing FFT implementations for specific hardware architectures, such as CPUs, GPUs, or specialized signal processing units, further enhances performance and scalability. By leveraging these optimizations and advancements, developers can harness the full potential of FFT for tackling complex signal processing tasks in diverse domains.

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